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USE OF LARS SYSTEM FOR THE QUANTITATIVE
DETERMINATION OF SMOKE PLUME LATERAL DIFFUSION
COEFFICIENTS FROM ERTS IMAGES OF VIRGINIA

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Abstract

A technique for measuring smoke plume of large industrial sources observed by satellite using LARSYS is proposed. A gaussian plume model is described, integrated in the vertical, and inverted to yield a form for the lateral diffusion coefficient, K_y . Given \bar{u} , wind speed; y_1 , the horizontal distance of a line of constant brightness from the plume symmetry axis a distance x_1 , downstream from reference point at $x=x_2$, $y=0$, then $K_y = \bar{u} y_1^2 / 2x_1 \ln(x_2/x_1)$. The technique is applied to a plume from a power plant at Chester, Virginia, imaged August 31, 1973 by ERTS I. The plume bends slightly to the left 4.3 km from the source and estimates yield K_y of $28 \text{ m}^2 \text{ s}^{-1}$ near the source, and $19 \text{ m}^2 \text{ s}^{-1}$ beyond the bend. Maximum ground concentrations are estimated between 32 and 64 ug m^{-3} . Existing meteorological data would not explain such concentrations.

List of Symbols

x	= distance down wind from plume effective source
y	= horizontal distance from plume symmetry axis
z	= vertical distance from plume symmetry axis
Q	= mass per unit time of effluent emitted
\bar{u}	= mean scalar wind speed
$\Psi(x_1 y_1 z)$	= concentration of effluent as mass per unit volume

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R. N. Blais, G. E. Copeland and T. H. Lerner

- K_y = lateral effective diffusion coefficient
 ($l^2 t^{-1}$)
- K_z = vertical effective diffusion coefficient
 ($l^2 t^{-1}$)
- r = $(x^2 + y^2 + z^2)^{1/2}$
- $\phi(x, y)$ = columnar loading in vertical in mass per unit
 area
- P_{ij} = number of i^{th} pixel in scan line j on ERTS
 image
- λ_j = number of j^{th} scan line on ERTS image
- D_{ijkl} = distance in meters from P_{ij} to P_{kl} in config-
 uration space
- α_{ijkl} = compass bearing from ground point P_{kl} to P_{ij}
 in configuration space at latitude = 37°

Introduction

Remote sensing techniques have been applied to the study of smoke plumes from fixed industrial point sources in an effort to verify numerical smoke plume dispersion models. In previous papers^{1,2} the value of such studies was discussed, together with techniques that would apply to aerial photographs of plumes. In brief, such studies can aid in the development and refinement of plume dispersion models that combine stack and effluent parameters, with meteorological, or climatological data as input, and that yield ground level deposition patterns for use in air pollution control schemes and in environmental impact studies of new industrial sources. In addition, if such models exist, they can be inverted so that comparison with images of smoke plumes can yield valuable insights to regional pollution transport, wind trajectories, and vertical stability at the time the image was acquired. This is obviously useful during pollution episodes, or during field experiments.

The current study extends previous work by changing from aircraft to satellite platform (ERTS-I, recently renamed LANDSAT I) imagery, and by applying computer techniques to the analysis of the digitized imagery itself. To do this, use was made of the LARSYS software developed by the Laboratory for Applications of Remote Sensing (LARS) at Purdue University, Lafayette, Indiana, and of a remote terminal located at the National Aeronautics and Space Administration's Langley Research Center (LRC), Hampton, Virginia. The terminal gave direct access to the LARS computer and databank at Purdue, and was jointly administered by LRC and by Old Dominion University of Norfolk, Virginia.

SMOKE PLUME DIFFUSION USING LARS

For the current study a detailed analysis was made of the image of a smoke plume (ERTS E-1404-15190) as it appeared (Cf. Fig 1) about 10:00 EST, August 31, 1973. The plume arises from a steam-electric generating plant in Chester, Virginia, operated by the Virginia Electric Power Company (VEPCO), and it can be followed on the image toward the northwest about 18 kilometers. An estimate was made of the lateral diffusion coefficients as measured from the image. Some anomalous meteorological conditions were examined, including an interesting large scale bend in the plume, and the fact that the wind field as reported by the nearest available meteorological stations was at odds with the observed behaviour of the plume. Finally, the plume model was run using the data acquired from the image, and estimates of ground deposition were made.

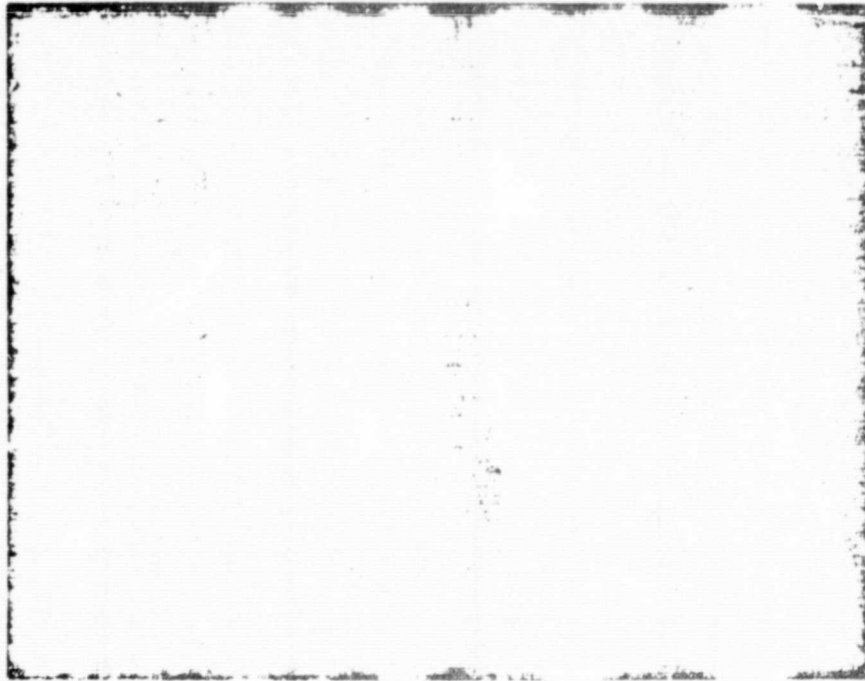


Fig. 1 Smoke plume at Chester, Virginia, 10:00 EST, as seen by ERTS MSS 4 (LARS channel 1), 31 August 1973. North is toward the top. The light vertical region branching from the plume middle is a ground feature (Army Munitions Depot).

Analytical Techniques

The plume model used will be briefly described outlining its required input parameters, its limiting assumptions and the forms of output it can produce. Next the type of data available through LARS will be described. Finally, two problems in relating the model to the LARS satellite data, spatial rectification of the LARS printout and computation of lateral diffusion coefficients, will be outlined.

Plume model. The computer plume model attempts to solve a turbulent diffusion equation for a time invariant point effluent source in a wind field. The input data required is in two categories--stack and meteorological parameters. Stack parameters, available from the State Air Pollution Control Board, include stack height and diameter, and the velocity, temperature, and mass flux of the effluent. Meteorological parameters include mean wind direction and speed, surface temperature and lapse rate. Standard empirical formulas can be applied to those data to determine an "effective stack height" for the plume.³ The plume's effective source point is usually somewhat above the true stack height due both to the vertical effluent momentum and to its buoyancy as it enters colder ambient air.

The mathematics of the turbulent diffusion equation, and its approximate solution, sometimes called the gaussian plume model, is covered in a variety of texts.^{4,5} Some of its salient features will be described here. First, it assumes that the situation is steady state, both for stack and meteorological parameters. This assumption is frequently valid, but often variability in winds causes the solution to be valid only on a time average basis. Second, it is assumed that in any vertical plane normal to the mean wind vector the concentration distribution of effluent is elliptically distributed about the plume's symmetry axis with the major and minor axes aligned in horizontal and vertical directions. Third, it is assumed that the concentration falls off in any such plane along any vertical or horizontal line as a gaussian distribution centered at the major or minor axis of the ellipse. This assumption is only valid if a set of effective turbulent diffusion coefficients can be determined such that the lateral coefficient, K_y , and the vertical coefficient, K_z , are both independent of spatial and temporal coordinates and such that the downwind coefficient, K_x , is zero to first order. Boundary conditions are applied forcing concentrations to zero at large distances from the source. No effluent sinks are considered. The mass flux out the stack, Q equals $\bar{v}\bar{u}$

SMOKE PLUME DIFFUSION USING LARS

integrated over any plane normal to the plume's symmetry axis. Concentrations then can be described as

$$\Psi(x,y,z) = (Q/4\pi\bar{u}(K_y K_z)^{1/2}) \exp((-u/4x)(y^2/K_y + z^2/K_z))$$

While K_z can be estimated from meteorological conditions (lapse rate, wind sheer, etc.) the determination of K_y is almost impossible from a priori considerations.

Several output forms are available from the model. One plots the concentration along any plane orthogonal to any coordinate. A second provides an output that is called the columnar loading, Φ , the definite integral of Ψ from minus infinity to plus infinity over z , which is related to brightness observed from a satellite. This is given by:

$$\Phi(x,y) \cong (Q/(4\pi\bar{u}K_y x)^{1/2}) \exp(-\bar{u}y^2/4xK_y)$$

Finally, the model is capable of superimposing multiple plumes of differing stack parameters and locations, and of modifying downwind meteorological conditions.

LARS data. While the LARS system has a variety of software, only certain ones of the less sophisticated algorithms were employed. These included the LINEGRAPH, COLUMNGRAPH, and PICTUREPRINT programs. The LINEGRAPH program will take any scan line of any spectral band, and will prepare a graph of the radiance as a function of pixel (picture element) number along the scan line. The COLUMNGRAPH feature plots radiance versus scan line number for a given pixel number. Finally, PICTUREPRINT prepares a greyscale map of a region in a single ERTS spectral band with an option to assign up to 16 symbols to 16 different grey scale domains specified by the user. When used in conjunction with auxiliary programs (HISTOGRAM and GRAPHISTOGRAM) it is possible to density slice the map in such a way that background is completely suppressed (i.e. printed as a blank), while a feature of interest (e.g. a smoke plume) is printed in several symbols representing differing regions of brightness or reflectivity. Figure 1 shows such a printout though photoreduction for publication has made it hard to distinguish the different symbols. Lines of constant brightness can then be projected on the horizontal plane, and the first two graphing programs can be used to determine inflection points on the spatial brightness curve, yielding lines of maximum contrast that can be superimposed by hand on the grey scale map.

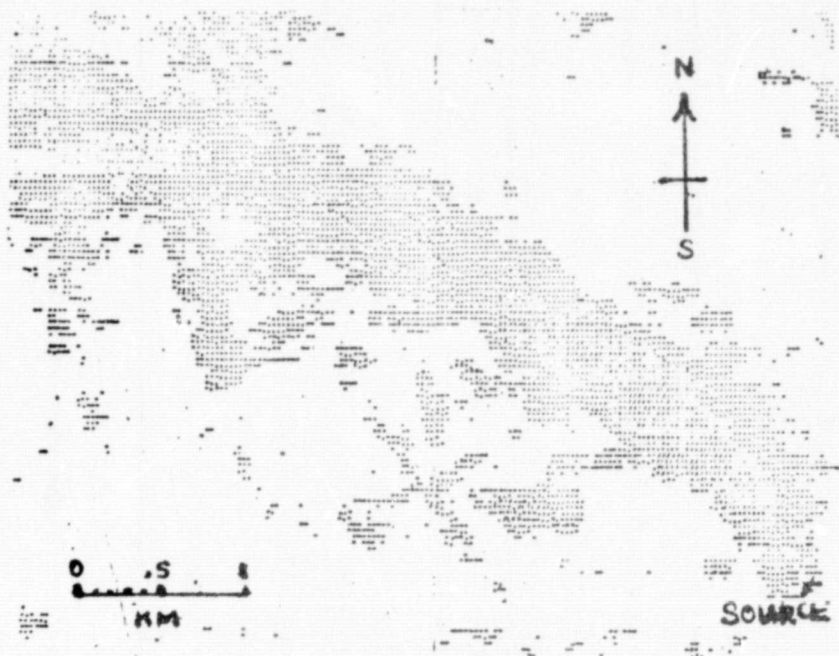


Fig. 2 LARSYS PICTUREPRINT of smoke plume.
ERTS MSS 4 (LARS 1)

LARSYS PICTUREPRINT Spatial Rectification. The grey scale maps printed by the LARS System (LARSYS) are spatially distorted. ERTS is in a near polar orbit at 99° to equator. Thus, the ground track is not along lines of constant longitude. The MSS scans perpendicularly to the ground track of the satellite. Thus the MSS image is a parallelogram projected on the earth's surface. In any given line a pixel of a certain number represents a point slightly west of the point due south of the similarly numbered pixel in the preceding line. The computer's printer inherently prints pixels of identical number directly beneath one another. Moreover, the number of typed symbols per line, and lines per inch do not correspond directly to the actual ground scene spacing of areas represented by pixels and lines. To correct these problems, three simple formulas were developed so that true distances and compass bearings could be determined from a LARSYS PICTURE-PRINT. Select two pixels P_{ij} and P_{kl} on scan lines j and l , then the actual distance in meters, D_{ijkl} , between the two points on the ground is given by

$$D_{ijkl} = (79m)((\lambda_l - \lambda_j)^2 + (P_{ij} - P_{kl})^2(0.494))^{\frac{1}{2}}$$

SMOKE PLUME DIFFUSION USING LARS

The azimuthal angle, α_{ijk1} , in degrees measured to the east of north between the two pixels is then

$$\alpha_{ijk1} = 10^\circ + \tan^{-1}((p_{ij} - p_{kl})(0.70)/(\lambda_1 - \lambda_j))$$

Finally, we will be interested in measuring horizontal plume widths on grey scale maps along lines perpendicular to the downwind symmetry axis of the plume. Thus, given two pixels, p_{ij} and p_{kl} , on that symmetry axis, we would like to find another pixel, p_{mn} , in any line, l_n of our choosing that represents a point on a line passing through p_{ij} perpendicular in configuration space to the plume axis. This is given by

$$p_{mn} = p_{ij} + (2.02)((\lambda_n - \lambda_j)(\lambda_1 - \lambda_j)/(p_{ij} - p_{kl}))$$

Theory for determination of the lateral diffusion coefficient. In a previous publication² measurements of lateral diffusion coefficient by eye from aerial photos were reported. The eye detects the "shape" of the plume as the line of maximum contrast between plume and background, and not as a line of constant brightness. In that case it was reported that the shape of the line of maximum concentration is parabolic, with the apex at the source, and in accordance with the model it satisfies the formula:

$$y = (2K_y x / \bar{u})^{1/2}$$

Through the LARSYS PICTUREPRINT program it is possible to determine lines of constant brightness. We may assume these are related to lines of constant columnar loading, as long as the plume is not opaque, and is of sufficiently low concentration for multiple light scattering events to be insignificant. The shape of such a line can be derived from Eq2 by setting $\phi(x_2, 0) = \phi(x_1, y_1)$. The result is

$$\frac{1}{2}Q(\pi \bar{u} K_y x_2)^{-1/2} \approx \frac{1}{2}Q(\pi \bar{u} K_y x_1)^{-1/2} \exp(-\bar{u} y_1^2 / 4 x_1 K_y)$$

This can be solved for the contour of lines of constant brightness.

$$y_1 = ((2x_1 K_y / \bar{u}) \ln(x_2/x_1))^{1/2}$$

Such lines form closed contours (Cf Fig. 3) and if x 's and y 's can be determined experimentally from measurements on a gray scale map one can solve for K_y

$$K_y = \bar{u} y_1^2 / (2x_1 \ln(x_2/x_1))$$

R. N. Blais, G. E. Copeland, and T. H. Lerner

Thus, in theory, the lateral diffusion coefficient can be measured.

Practical considerations. Due to the fact that a real, turbulent plume is being interpreted with the aid of an idealized time averaged model, it is insufficient to use one set of data points (x's and y's) to determine the lateral diffusion coefficient. A graphic overlay technique is used to smooth data so that a series of data points are used to determine an average value of K_y . In essence, a plume symmetry axis is drawn on the gray scale map by eye. Second, a series of lines perpendicular to it are marked out using the spatial rectification procedure. Then a smooth outline of the plume's lines of constant brightness are sketched. Widths are measured as a function of downwind distance, K_y 's are computed and averaged. These are then used as input to the plume model.

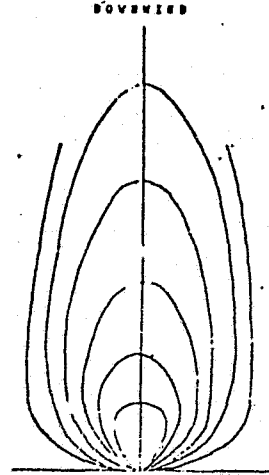


Fig 3. Lines of constant brightness as seen from above.

One other point is that different ERTS spectral bands give different results. This is to be expected since the ability of smoke particles to scatter light is strongly dependent on particle size and optical wave length. ERTS band 7 (LARS band 4) in the near infra-red (0.8 - 1.1um) cuts through haze readily, and frequently a plume that is very visible in another band is almost undetected in band 7. This may prove to be a useful tool for obtaining a crude size distribution for plume aerosols.

Analysis of the Chester, Virginia, Plume

A beautiful example of an industrial smoke plume was imaged by ERTS-1 on Friday, August 31, 1973, arising from an oil fired power generating station at Chester, Virginia. All input information needed to run the model could be obtained, and the image was taken with ideal atmospheric conditions. Thus, it was decided to analyze the case in detail. The source of the plume will be described, as will the meteorological conditions. A peculiar bend in the plume will be briefly discussed, then lateral diffusion coefficients will be estimated. Finally, the results of

SMOKE PLUME DIFFUSION USING LARS

the plume model run using these values of K_y will be discussed.

Plume source. The power plant at Chester, Virginia is located on the south bank of the James River, 17 km NNE of Petersburg, and 19 km SSE of Richmond. The plant has six smoke stacks. The height, h ; internal diameter, I.D.; effluent efflux velocity, v ; effluent temperature, T ; and rate of fuel (No. 6 oil) consumption, f , are tabulated below.

Stack	$h(m)$	I.D.(m)	$v(ms^{-1})$	$T(^{\circ}C)$	$f(kgs^{-1})$
1	61	3.7	12	197	5.91
2	61	3.7	15	174	7.96
3	61	4.0	14	142	9.75
4	61	4.0	22	162	15.0
5	61	5.2	23	130	29.3
6	61	6.1	33	128	58.9

Meteorological conditions. The analysis of meteorological conditions at the time the plume was imaged presents a conundrum, because the reports of the nearest stations indicate a situation at odds with the observed plume behavior. Eastern Virginia was under the influence of a weak high pressure system with associated light breezes. Winds reported at Richmond were calm at 9:58 EST and reached 7 knots from 200° (SSW) at 10:56 EST. The satellite imaged the scene at 10:14 EST (15:14 Z). From sunrise until 9:58 EST, the temperature had risen rapidly from 69°F to 89°F at a rate of about 5°F/hour, but from 9:58 EST until 10:56 EST the temperature rose only 2°F, and during the following hour it failed to rise at all. Such behavior would indicate that a weak diurnal inversion persisted over the region until the morning insolation caused sufficient heating of the earth's surface to warm the lower layer of air. When the inversion broke up, sometime between 9:58 EST and 10:56 EST a much thicker mass of air had to be heated resulting in the decreased rate of temperature increase. Though no radiosondes are flown from Richmond, the nearest ones (from Wallops Island, Virginia, and from Washington, D. C.) do indicate the presence of such an inversion that morning.

The presence of this inversion, and its breaking up, is in accord with the observed plume behavior, but the wind directions are not. All surrounding stations reported winds out of generally southwesterly directions, yet the plume

R. N. Blais, G. E. Copeland, and T. H. Lerner

clearly was heading off toward the northwest, thus being blown by southeasterly winds. The significance of this fact will be discussed in the conclusions, while the accord with the inversion will be discussed in the next section.

Bend in Plume. An obvious feature of the plume is that it bends. Starting from the source, the plume heads 4.3 km at an azimuth of 305° , then turns westward at 272° . At first this bend was assumed to indicate the rise of the plume to a higher altitude with differing flow direction, but this peculiar bend to the left was not consistent with the tendency of winds at higher altitudes to blow at an angle to the right of the surface winds. The idea was proposed to the authors by Herman Wobus and Earl Kindle that the bend did not represent a spatial variation in the wind-field, but rather a temporal one. Prior to approximately one half hour before the image was acquired, the wind did blow from the east carrying the plume away from the source at 272° . Then it shifted to a more southeasterly wind that carried the effluent subsequently discharged off in a bearing of 305° . This wind shift is associated with downward momentum transfer after the breaking up of the inversion. But significantly, the new wind direction carried the older plume, still with its symmetry axis oriented at 272° bodily off at 305° . This changed the K_y value obtained for portions of the plume farther from the source than 4.3 km from the value obtained closer to the source. Thus, two different lateral diffusion coefficients were to be expected for the two regimes. Wobus predicted, in fact, that a smaller K_y in the more distant portion of the plume could allow higher concentrations to occur at the bend point (a virtual source) than would be experienced closer to the real stack. Superficially, an examination of the greyscale maps indicated a region of enhanced brightness was indeed present, but it has so far been impossible to definitively establish that it is not related to a ground feature, a large military depot, that is unfortunately right beneath the bend. A LARSYS CLASSIFYPOINTS program did remove the background feature leaving the bright downstream region, but its photometric interpretation is difficult. When the two values of K_y determined from the imagery were inserted in the plume model, it did display the feature Wobus predicted.

Determination of Lateral Diffusion Coefficients. The coefficients determined by the method above can be determined as a function of wind speed. Between the source and the bend care had to be exercised to not allow the multiple stacks to confuse the issue by causing an apparent

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SMOKE PLUME DIFFUSION USING LARS

broadening of the plume that would be interpreted as an excessively large value of K_y . Thus, only a limited number of points of adequate downstream distance could be used. The mean value was determined to be $K_y = 11.6 \text{ (m)} \bar{u} \pm 0.6 \text{ (m)} \bar{u}$. In the region beyond the bend more numerous measurements lead to values of $K_y = 8.0 \text{ (m)} \bar{u} \pm 1.6 \text{ (m)} \bar{u}$.

Wind speeds were now estimated by noting that the bend in the plume is 4.3km from the source. The meteorological data indicated the inversion was breaking up around the time of the last observation at 9:58 EST. Assuming the wind shifted about a half hour before the satellite pass, the wind speed would have to be approximately 8.6km per hour, or to one significant figure 6 knots. This makes the values of diffusion coefficient between source and bend $K_y = 28 \text{ m}^2 \text{ s}^{-1}$. This value is probably overestimated due to apparent broadening of multiple sources. Assuming a similar windspeed beyond the bend, the value would be $K_y = 19 \text{ m}^2 \text{ s}^{-1}$. Both these values are of course based on crude assumptions.

Model predicted ground concentrations. Inserting the above values into the plume model, together with stack and meteorological parameters, the following output (Fig 4) was produced. Concentrations at ground level are printed on a binary exponential scale, such that a 2 indicates 2^2 ugm^{-3} , and a 5 would indicate 2^5 ugm^{-3} , etc.

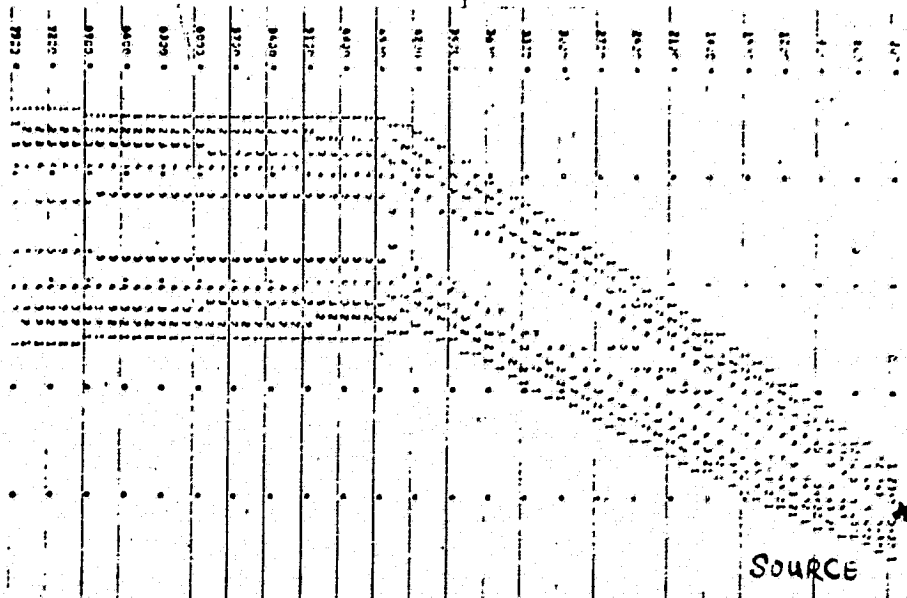


Fig 4 Printout of ground concentration in ugm^{-3} on binary exponential scale. Vertical lines measure distance downstream from the source in 100m units.

R. N. Blais, G. E. Copeland, and T. H. Lerner

Maximum ground concentration inside the region marked 5 would be greater than 2^5 or 32 ugm^{-3} , but less than 2^6 or 64 ugm^{-3} .

Conclusions

The application of satellite imagery to the analysis of smoke plumes has shown that useful data can be acquired that could not be assembled in any other way. First, anomalously high particulate pollution levels that would potentially be recorded by surface air quality stations would have been attributed to the wrong cause on the test day simply because the nearest meteorological stations reported different wind directions. Consequently, local air pollution models for urban regions that depend on a limited number of reporting stations should be checked against remotely sensed data to identify the extent and frequency of such anomalous behavior. Second, the smoke plume itself records a temporal history of the day's meteorological conditions, filling in gaps in locally recorded data. Finally, if emission parameters are known satellite data can lead to reasonable estimates of surface loading due to a plume simply by seeing its apparent geometric shape.

Acknowledgements

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SMOKE PLUME DIFFUSION USING LARS

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